R2E – IS IT STILL AN ISSUE?

S. Danzeca †, M. Brugger, A. Masi, S. Gilardoni, CERN, Geneva,

Abstract

The R2E ("Radiation to Electronics") project [1] mandate is to follow up on the equipment failures related to radiation and propose mitigation strategy. In this respect, 2015 LHC operation has continued to provide valuable inputs for the detailed analysis of radiation levels and radiation induced equipment failures. An overview of the mitigation strategy from the 2011 up to the 2015 is necessary to highlight the improvement obtained in terms of failure rate. The causes of failure, the radiation levels around the LHC and the mitigation actions of the 2015 run are analysed and their future impact on operation in terms of failure rate are reported in this work.

INTRODUCTION

The R2E mitigation strategy effects can be dated back in the 2011. Several shielding campaigns and 'on the fly' relocation had been set up before the 2011 in order to reduce the failure rate in the shielded areas and in the tunnel. In the 2011 twelve dumps per fb^{-1} due to the radiation effects were recorded and they caused around 400 hours of down time [2]. During the Christmas break of the same year several actions of relocations, shielding and equipment upgrades have been carried out in order to further reduce the impact of the radiation on the electronics. The effectiveness of these actions was visible during the 2012 run. The number of dumps during that year was 3 dumps per fb^{-1} corresponding to around 250 hours of downtime [3].

The final relocation and shielding were planned for the LS1 aiming at reducing the failure rate at around 1 dump per fb^{-1}. The plan was also to support new radiation tolerant developments and foresee the installation of this new equipment between the LS1 and LS2. Thanks to the new radiation tolerant developments the target would have been 0.5 dumps per fb^{-1} as a requirement for nominal (and beyond) LHC operation. This work aims at understanding the achievement obtained up to today and what has still to be done in terms of mitigation and prevention. For this scope, the knowledge of the radiation levels around LHC critical areas and the LHC tunnel is fundamental. The radiation levels of the 2015 run are compared with the 2012 measurements to highlight the effect of the accelerator parameters such as the bunch spacing. In the second paragraph, the equipment failures of the 2015 operation are analysed for the critical equipment in the tunnel and the foreseen failure rates are reported for the 2016/2017, considering expected radiation levels.

RADIATION LEVELS AND PARAMETERS SCALING

The radiation-induced failures on electronic equipment observed during 2015 LHC operation are mainly Single Event Effects (SEE). The probability of having a SEE is proportional to the cumulated High Energy Hadron (HEH) fluence. The radiation levels in the LHC tunnel and in the shielded areas have been measured using the RadMon system [4]. The HEH fluence measurement is based on the reading of the Single Event Upsets (SEU) of SRAM memories whose sensitivity has been previously calibrated at various facilities [5] [6]. The LHC radiation levels depend on the operational parameters because of the peculiarity of the three main categories of radiation sources at LHC: (a) direct losses in collimators and absorber like objects, (b) particle debris from beam-beam collisions in the four main experiments, and (c) interaction of the beam with the residual gas inside the beam pipe.

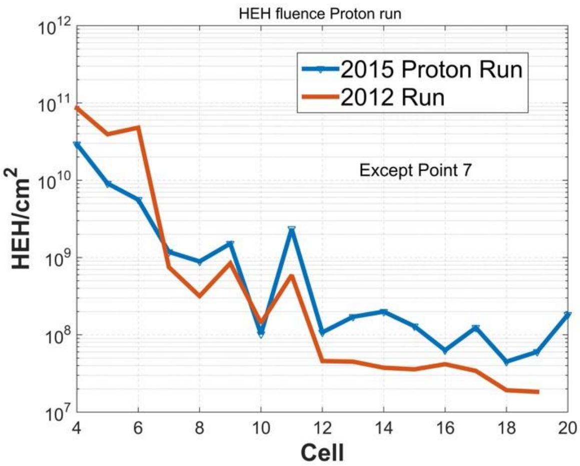

Figure 1: Radiation levels expressed as HEH fluence for the cells from 4 to 20 considering all the LHC points except the 7.

The main difference between the 2012 operation and the 2015 operation is the 50 ns and 25 ns bunch spacing respectively. The HEH hadron fluences are calculated per each cell considering all the points together (apart from point 7). The HEH fluences measured by the RadMons in the LHC tunnel are depicted in Figure 1 considering only the proton run. Comparing the 2015 and 2012 levels, for the cells above the number 8, the HEH fluence in the 2015 is higher than the ones of the 2012 of around a factor 3 to 4. This has to be considered a direct impact of the 25 ns operation that, as expected, generates higher beam-gas interactions. On the other side, for cells below the number 8, the radiation levels are proportional mainly to the integrated luminosity and thus, the HEH fluence cumulated over the 2015 (corresponding to ~4 fb^{-1}) is lower of a factor ~4 than the one cumulated during the 2012 (~20fb^{-1}).

The HEH fluences for the most critical shielded areas where electronic equipment is or was installed are reported in Table 1. In Table 2 the predicted values of the radiation levels are compared to the measured ones showing a good agreement.

Table 1: Measured HEH fluence in critical shielded areas in 2012 and 2015.

Critical Areas	Measured 2012	Measured 2015
	HEH/cm^2	HEH/cm^2
UJ14/16	1.10E+08	6.82E+07
RR13/17	1.80E+07	1.44E+07
UJ56	1.20E+08	9.77E+07
RR53/57	1.80E+07	9.17E+06
UJ76	5.50E+07	9.75E+06
RR73/77	3.00E+07	1.57E+07

Usually, being the shielded areas close to the interaction point their radiation levels scale with the integrated luminosity. This statement is not valid for the UJ76 and RR73/77 where the radiation levels scale with the beam losses. Indeed, in the areas close to the collimators (i.e UJ76) the radiation levels can change drastically depending on the collimators settings [2-3].

Table 2: Measured HEH fluence in critical shielded areas in 2012 and 2015.

Critical Areas	Predicted 2015	Measured 2015
	HEH/cm^2	HEH/cm^2
UJ14/16	5.04E+07	6.82E+07
RR13/17	1.68E+07	1.44E+07
UJ56	4.24E+07	9.77E+07
RR53/57	2.64E+07	9.17E+06
UJ76	6.48E+06	9.75E+06
RR73/77	1.92E+07	1.57E+07

During the LS1, thanks to the R2E mitigation strategy all the sensitive equipment has been relocated in the UJs leaving few to none sensitive electronics.

It can be concluded that the present analysis nicely shows that (a) the radiation levels were correctly analysed and measured in the last run of operation; (b) an efficient monitoring system is an important asset in order to have an online mean of verifying radiation levels in order to control a possible impact on installed equipment. The results, obtained during 2015 LHC proton operation, show a very good agreement between the predictions and the measurements which are given with an uncertainty factor of 2.

FAILURES OBSERVED IN 2015 AND-CORRESPONDING MITIGATION ACTIONS

The main sources of information were the LHC e-logbook, the meeting on the LHC operation follow-up, daily held at 8h30 [7], the Accelerator Fault Tracker (AFT) tool [8] and via the Radiation Working Group (RADWG) [9]. During the year, the collaboration of all the equipment groups was highly appreciated and permitted to improve the performed failure analysis. Once a failure is suspected to be related to radiation effects, the type of failure, the location and the equipment affected are collected. In some cases, it is not clear whenever a failure was effectively due to radiation effects. Thus, the event is marked as to be confirmed and a further analysis is required to understand the reproducibility of the failure. While in the 2012 runs we had several destructive failures [ref], during the 2015 run all the events where 'soft' and the equipment did not require a replacement.

During LS1, all remaining possibly sensitive equipment has been moved from the critical areas (UJ14/16/56/76, US85, and UX45) to safer areas (mainly UAs and US); additional shielding has been installed in the RR areas to reduce further the radiation levels. These actions and several equipment upgrades made possible to reduce the number of failures for most of the equipment group.

Table 3 shows the failures due to the SEEs comparing the 2012 run and the 2015 after the Technical Stop 2 (TS2: week 36). Before this period, the statistics of the failures related to the radiation were dominated by the failure of the mDQQBS boards in the tunnel. These unexpected events caused by an untracked equipment changes with a very sensitive components [9] used on the quench protection system boards, have to be used as an alarm to not underestimate the radiation effects on the electronics. Nonetheless, in this work, these events are not analysed and the focus is on the events happened after the substitution of all the cards (after TS2).

Table 3: Number of failures due to radiation. **considering the RF failures

Equipment	Dumps 2012	Dumps 2015 (After TS2)
QPS	32	3
EPC	15	7
Cryo	4	0
EN/EL	1	0
Vacuum	4	0
Collimation	1	0
RF	3 (TBC)	4 (TBC)
Total	3 /fb^{-1}	2.3 /fb^{-1} (~3.4 /fb^{-1}**)

It is important to note that the number of events to be confirmed (RF equipment) represented a small part on the overall failures of the 2012 run, while for the 2015 these

events are an important fraction of the failures that is taken in consideration.
The failure rate normalized per fb^{-1} in the 2012 was 3 dumps per fb^{-1} while for the 2015 2.3 dumps per fb^{-1} without considering the RF failures (3.4 dumps considering the RF failures to be confirmed).
In the following subsections, the failure analysis and the envisaged mitigation actions for all the affected equipment groups are briefly summarized.

QPS

During the 2012 operation QPS equipment was the main cause of beam dumps for the LHC. The failures affected the equipment in the UJs, RRs and also the one close to the dispersion suppressors (DS). The signatures of the failures were multiple because of the diversity of equipment affected (i.e. the nQPS, the 600A protection systems). The equipment relocation, the firmware upgrades and the new radiation tolerant nDQQDI system deployed during the LS1 have proven to be effective reducing the beam dumps to only 3 in the 2015 run (after the TS2). The events were linked to the 600A protection system of which a new radiation tolerant version will be deployed during the YETS of the 2017. This new development will permit to reduce the number of failure drastically for the 2016/2017 runs.

EPC

The EPC equipment can be divided in the control part and power part. The events in the 2012 affected the 600A power supply, the FGC control cards and the 120A power supply. The AC/DC power supply problem has been corrected during the LS1 and a whatchdog fault have been corrected in the 2015. The 7 failures observed during the 2015 affected both the FGC and 120A circuit. The deployment of the radiation tolerant FGClite system is foreseen during the 2016/2017 YETS reducing the number of failures due to the control part. One destructive event was recorded in the 2012 while for the 2015 no events have been recorded.

RF

In the 2012 three RF events were recorded on a power supply and on vacuum gauges in UX45. These events have not be confirmed as radiation induced and in the 2015 no events happened on these devices. The 2015 events affected the ARC detector circulator/load and klystron window. Those cases might not be related to radiations. However, the fact that they happened in UX45, suggests keeping those events under investigations, and are noted here for completeness.

Others : Cryo, Collimation, EN/EL

The 2012 was characterized by several soft and hard events on some Cryogenics PLCs and Uninterruptible Power Supply (UPS) from EN/EL. The collimation system also suffered of a SEE on the control crate. This sensitive equipment has been relocated during the LS1. The relocation actions has been confirmed to be effective in the 2015 leading to no failures.

Taking into account those countermeasures and the expected radiation level, a very tentative estimation of the remaining failures for the 2016 is also given in Table 4. The EPC failures will still be the bottleneck during the 2016 operation leading to a failure rate of about 1-1.5 dumps/fb^{-1}. After the deployment of the FGClite during the YETS the remaining failures of the EPC will be only on the power part. This will permit to reach the target of 0.5 dumps/fb^{-1} for the 2017.
It's important to note that these previsions aims at trying to highlight the effectiveness of the mitigation measures, rather than aiming for accurate predictions of failures in the long-term Therefore, in order to assure this result, the R2E activities will continue with the established analysis process and also follow in detail the radiation levels. In this context, the long-term cumulative damages, as the Total Ionizing Dose (TID) effects, have to be considered.

Table 4: Expected number of failures due to radiation in the 2016/2017 considering 35fb-1 and 45fb-1 of integrated luminosity.

Equipment	Dumps 2016 ($35fb^{-1}$)	Dumps 2017 ($45fb^{-1}$)
QPS	0-5	0-5
EPC	~25	0-10
Cryo	0	0
EN/EL	0	0
Vacuum	0	0
Collimation	0	0
RF	?	?
Others	0-10	0-10
Total	~1-1.5 /fb^{-1}	~0.5 /fb^{-1}

CONCLUSION

A summary of the radiation levels and the induced failures for the LHC operation in 2015 has been reported. About 14 beam dumps were provoked by radiation effects (4 to be confirmed) during the 2015 run. The impact of the radiation effects would have been significantly higher without the countermeasures that were applied in the past years. Additional mitigation actions are planned for the YETS period to further reduce the radiation vulnerability of the equipment. The major change will be the deployment of the new radiation tolerant power supply controller which permits to lower the dumps due to radiation. Thanks to those efforts, the expected number of radiation induced dumps per fb^{-1} is expected to be <1 for the 2017.

The monitoring of the radiation levels will be a continuous job which aims at reducing the uncertainty factors, mainly related to the beam gas effects and the losses in the collimation areas, as well as to closely monitor the long-term radiation impact on exposed electronic systems. This will permit to verify the design assumptions and schedule preventive maintenance/rotation of the equipment when required. The detailed followup of the system upgrades and developments remains crucial to reach the above goal.

REFERENCES

[1] R2E website, www.cern.ch/r2e

[2] M. Brugger et al, "R2E Experience and Outlook for 2012", Proceedings of LHC Performance workshop, Chamonix 2012.

[3] M.Brugger et al, "R2E – EXPERIENCE AND OUTLOOK", Proceedings of 4th Evian Workshop on LHC beam operation.

[4] G. Spiezia et al. "The LHC accelerator Radiation Monitoring System - RadMON" http://pos.sissa.it/archive/conferences/143/024/RD11_024.pdf.

[5] K. Røed, M. Brugger, D. Kramer, A. Masi, P. Peronnard, C. Pignard, and G. Spiezia, "Method For measuring mixed field radiation levels relevant for SEEs in the LHC", Transactions on Nuclear Science, pp.1040-1047, Aug.2012.

[6] D. Kramer et al. "LHC RadMon SRAM detectors Used at Different Voltages to Determine the Thermal Neutron to High Energy Hadron Fluence Ratio", IEEE Trans. Nucl. Sci., vol. 58, no. 3, pp. 1117-1122, 2011.

[7] https://indico.cern.ch/category/6386/

[8] https://aft.cern.ch/#/home

[8] http://radwg.web.cern.ch/RadWG/

[9] S.Danzeca, "Alliance AS6C1008 and NEC D431000AGN SRAM Memory test report" https://edms.cern.ch/document/1685519/1